Impacts of Global Climate and Emission Changes on U.S. Air Quality

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Illinois State Water Survey (1895)

2003-2006

This research is funded by
U.S. EPA - Science To Achieve Results (STAR) Program
Grant # RD830963010

Acknowledgement

Federal grant

EPA Science to Achieve Results (STAR)

Supercomputing support

NCSA/UIUC, NOAA/FSL, NCAR

Illinois State Water Survey (1895)

2003-2006

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Objective

To quantify, and understand the uncertainties of, the individual and combined impacts of global climate and emission changes on U.S. air quality, from the present to 2050 and 2100.

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USA AQ Factors

U.S. air quality is determined by complex interactions over a range of spatial and temporal scales from (1) chemical processes and emissions on local to regional scales, (2) long-range transport of global pollutants and precursors, and (3) global and regional climate changes and variability.

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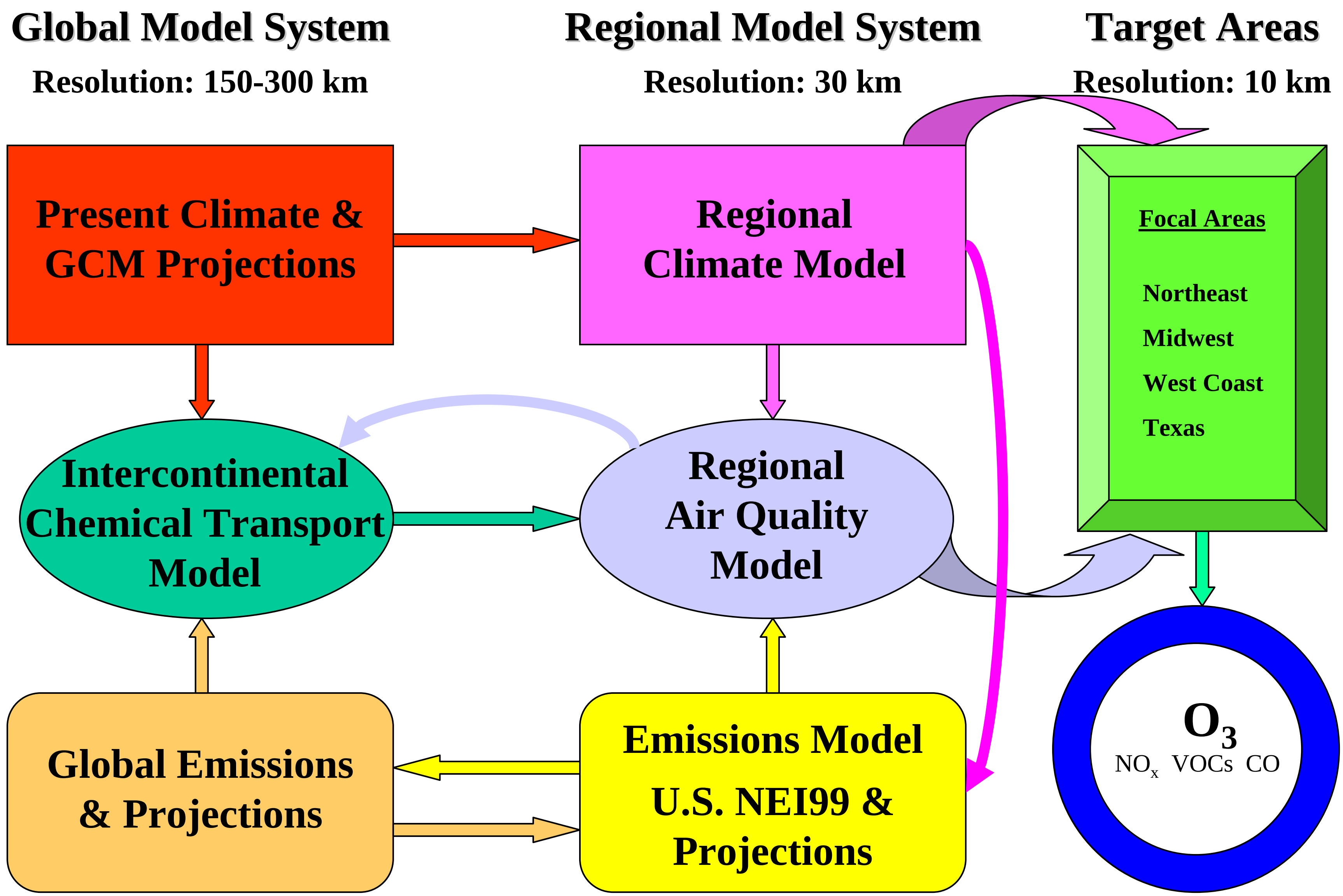

The nested global-regional modeling system: its components and their interactions

Uncertainty

- Biases in the climate and chemistry arising from the driving global models and the incomplete physics of the regional models
- Different climate sensitivities of the driving global models and the regional models
- Inconsistencies in the coupled global-regional modeling system
- Pollutant emissions error
- Natural variability

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Global Climate Models

- **LOW** climate sensitivity:

  Parallel Climate Model (**PCM**) of the National Center for Atmospheric Research/U.S. Department of Energy

- **HIGH** climate sensitivity:

  Hadley Centre third generation climate model (**HAD**)

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Future Projections

- PCM simulations for 2050 and 2100
  - A1Fi : high emissions scenario
  - B1: low emissions scenario

- HAD simulations for 2100
  - A2: intermediate high emissions scenario
  - B2: intermediate low emissions scenario

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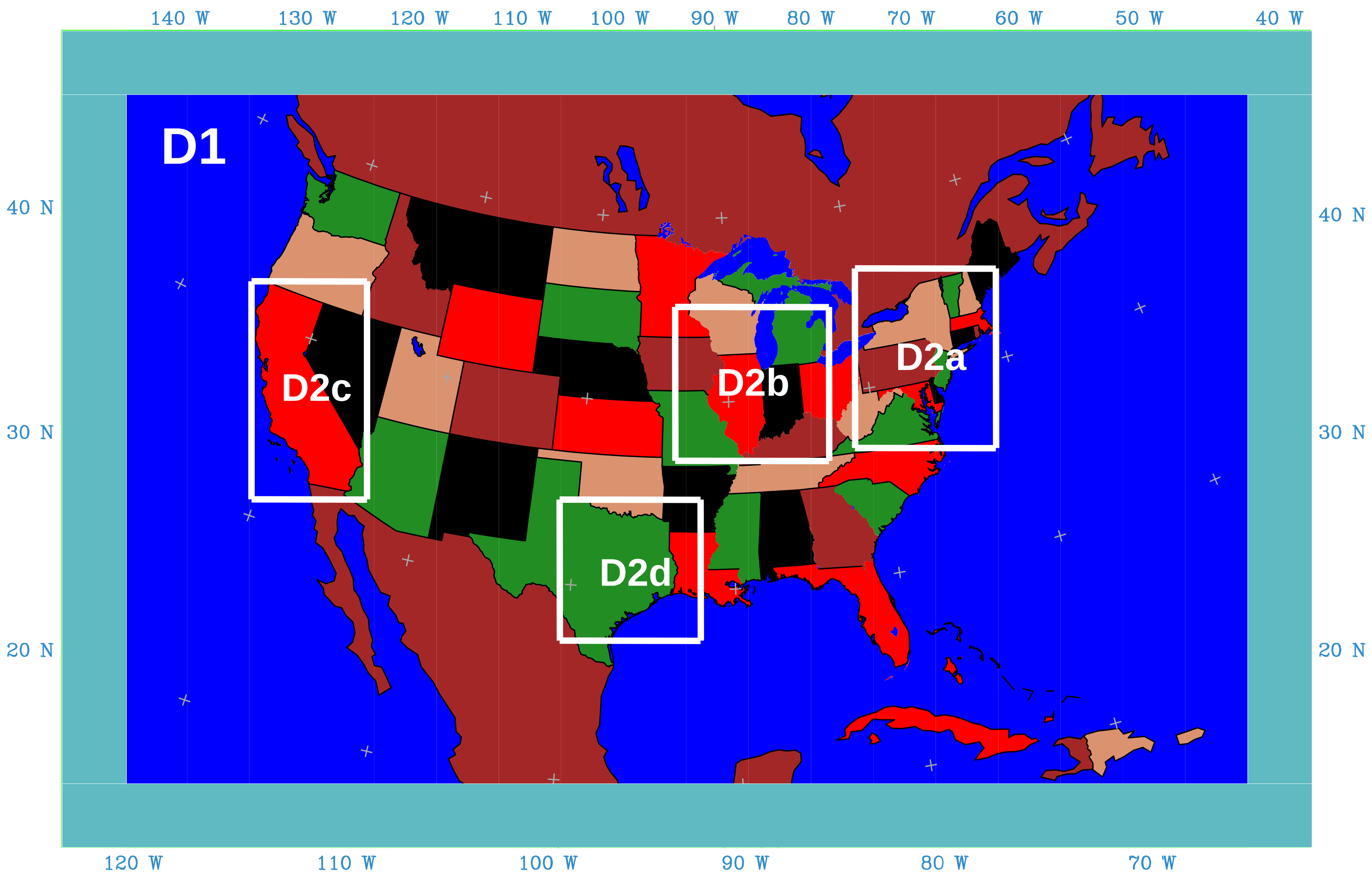
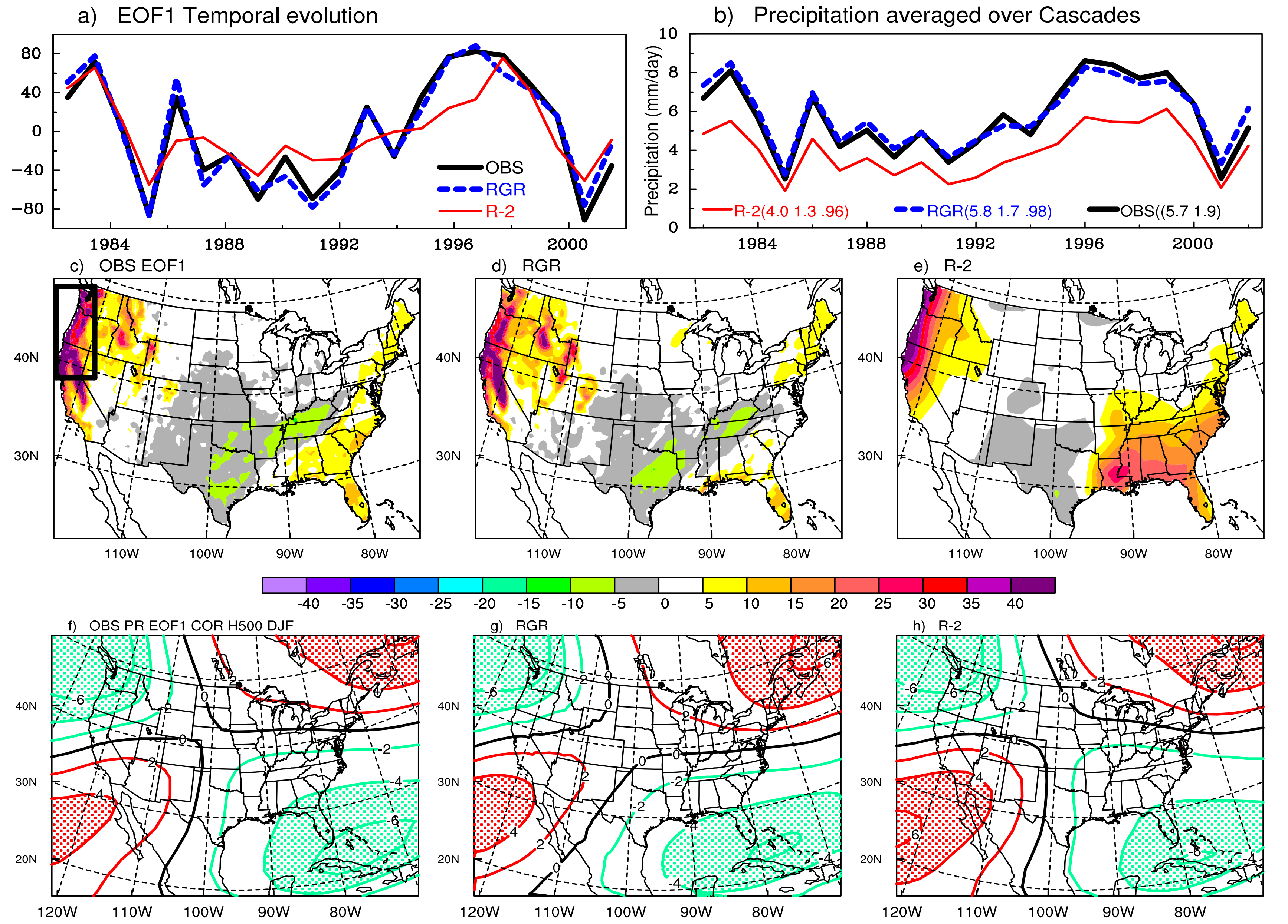
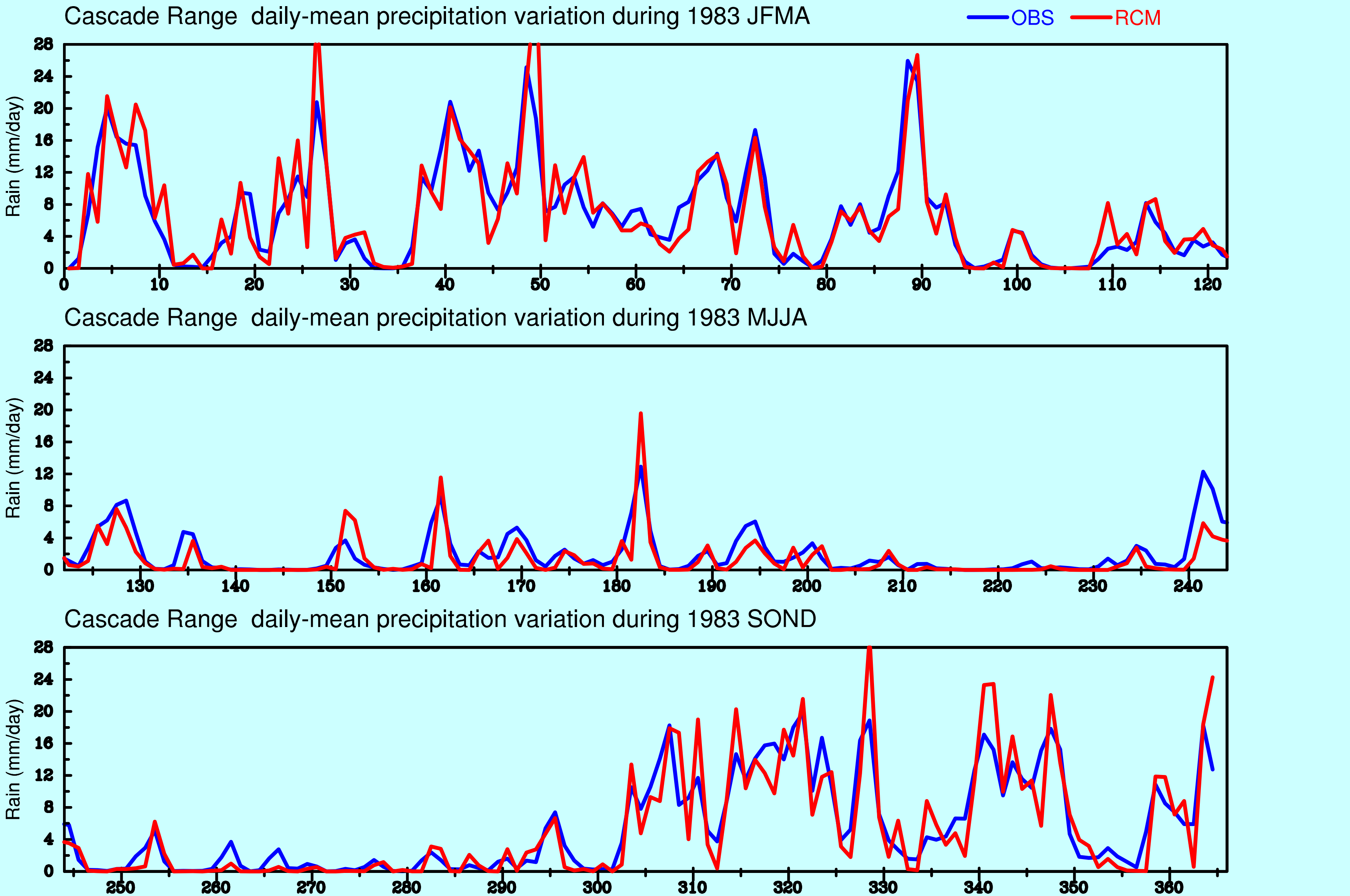


Regional computational domain design. The global models provide the regional models with lateral boundary conditions in the buffer zones (shaded outer edges). The climate model uses a grid spacing of 30-km over domain D1, while the air quality model uses 90-km in D1 and 30-km in subdomains D2a-d.

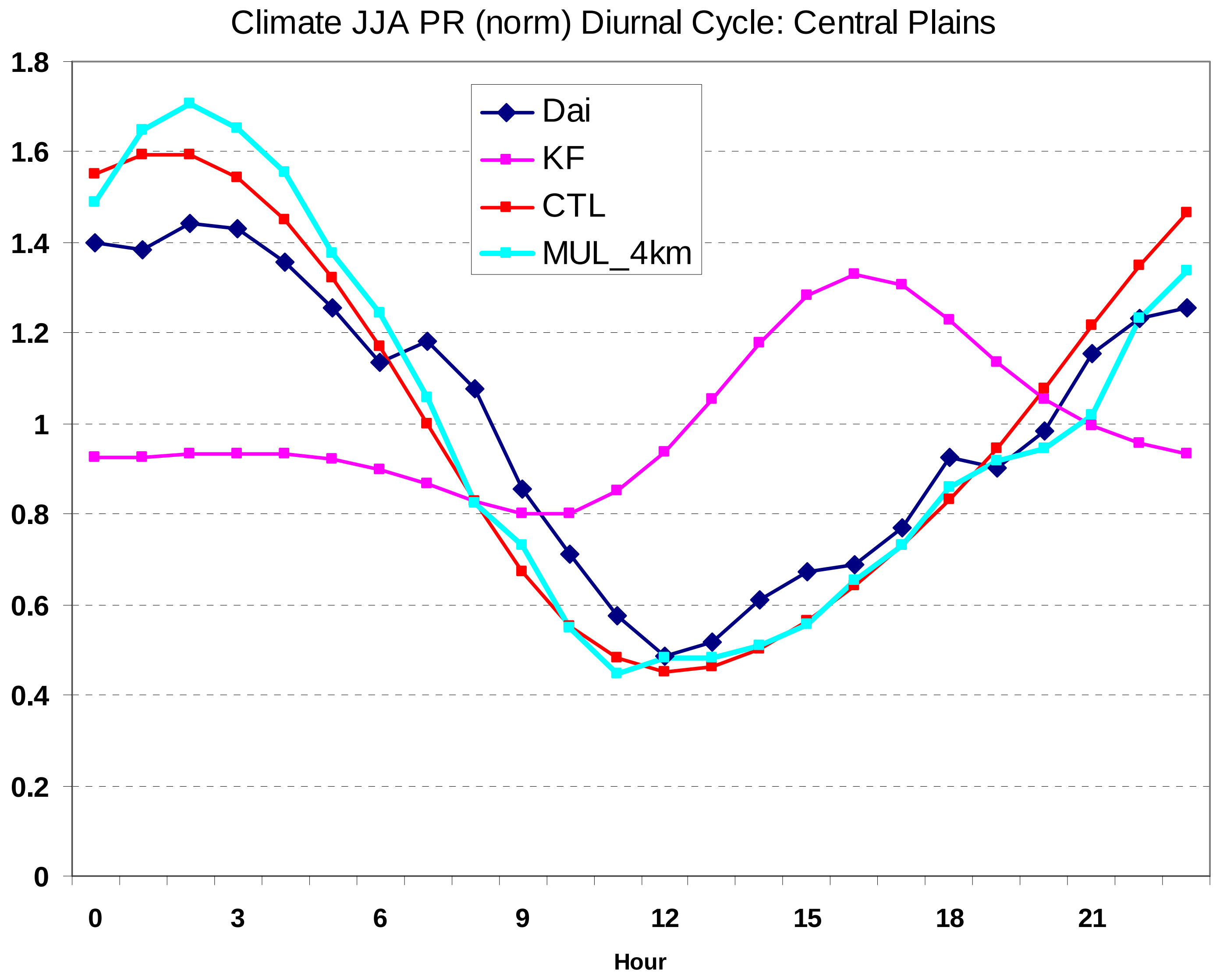
RCM Resolves Orographic Effects Better Than GCM



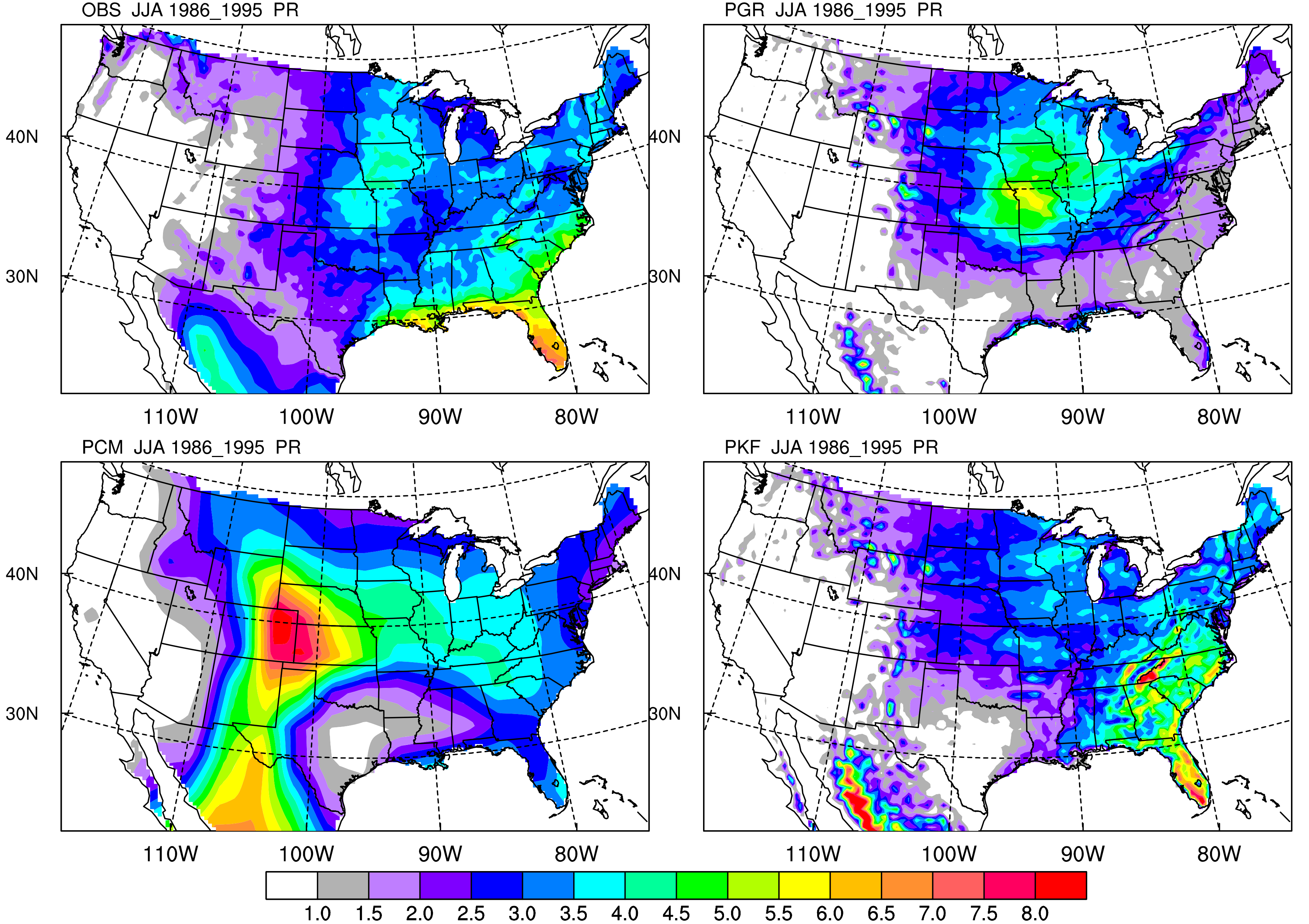
CMM5 Skill: Daily Fluctuations

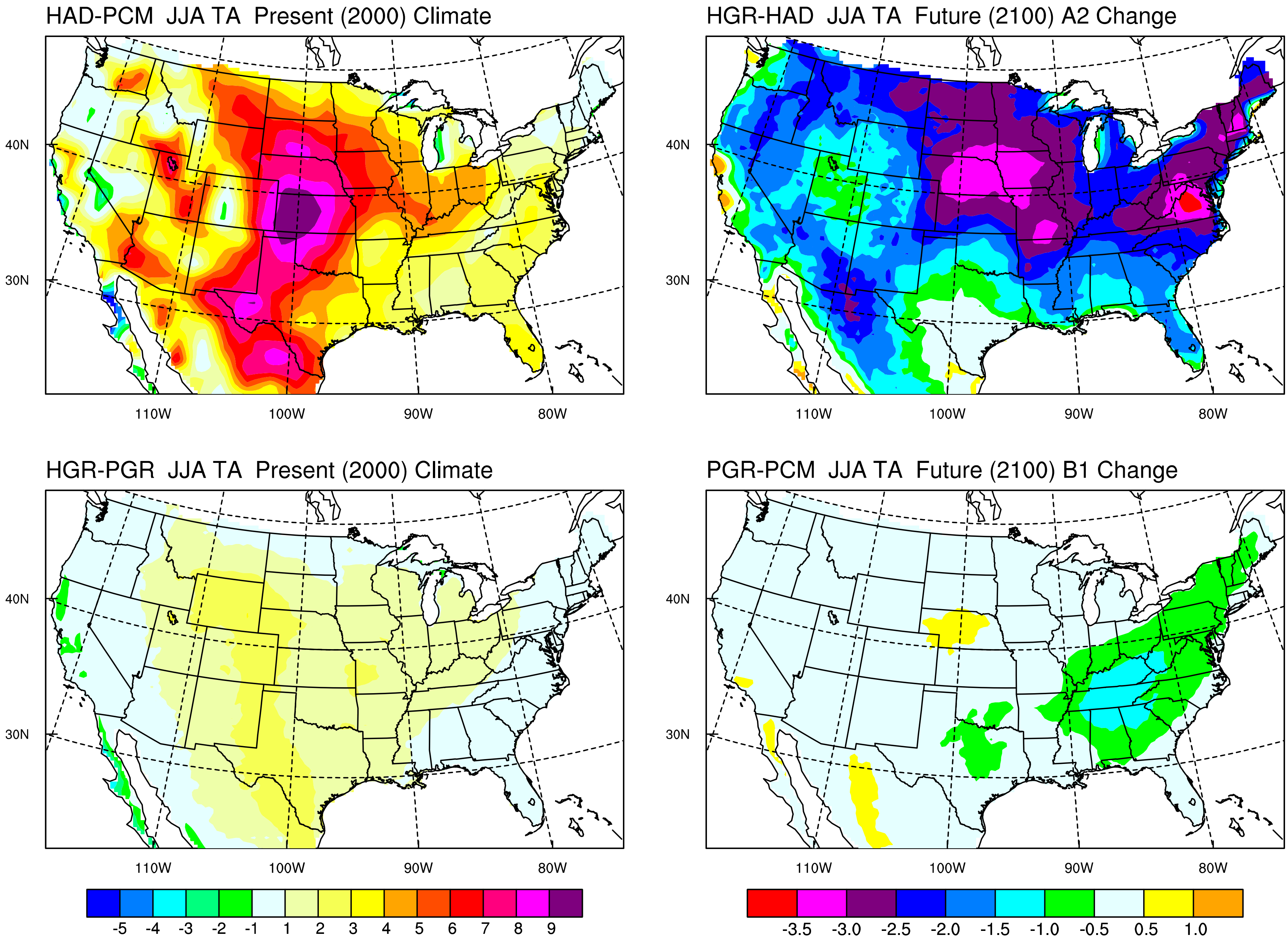


CMM5 Precipitation Diurnal Cycle



Much More Than That…




HAD-PCM JJA TA Present (2000) Climate
HGR-HAD JJA TA Future (2100) A2 Change
HGR-PGR JJA TA Present (2000) Climate
PGR-PCM JJA TA Future (2100) B1 Change
40N
30N
110W
100W
90W
80W
-5 -4 -3 -2 -1 1 2 3 4 5 6 7 8 9
-3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.5 1.0

Cumulus Sensitivity

The following examples show

- the sensitivity of the RCM downscaling to the cumulus parameterization for both the present-day climate simulation and future change projection

- emphasis the need for ensemble cumulus prediction in climate and air quality

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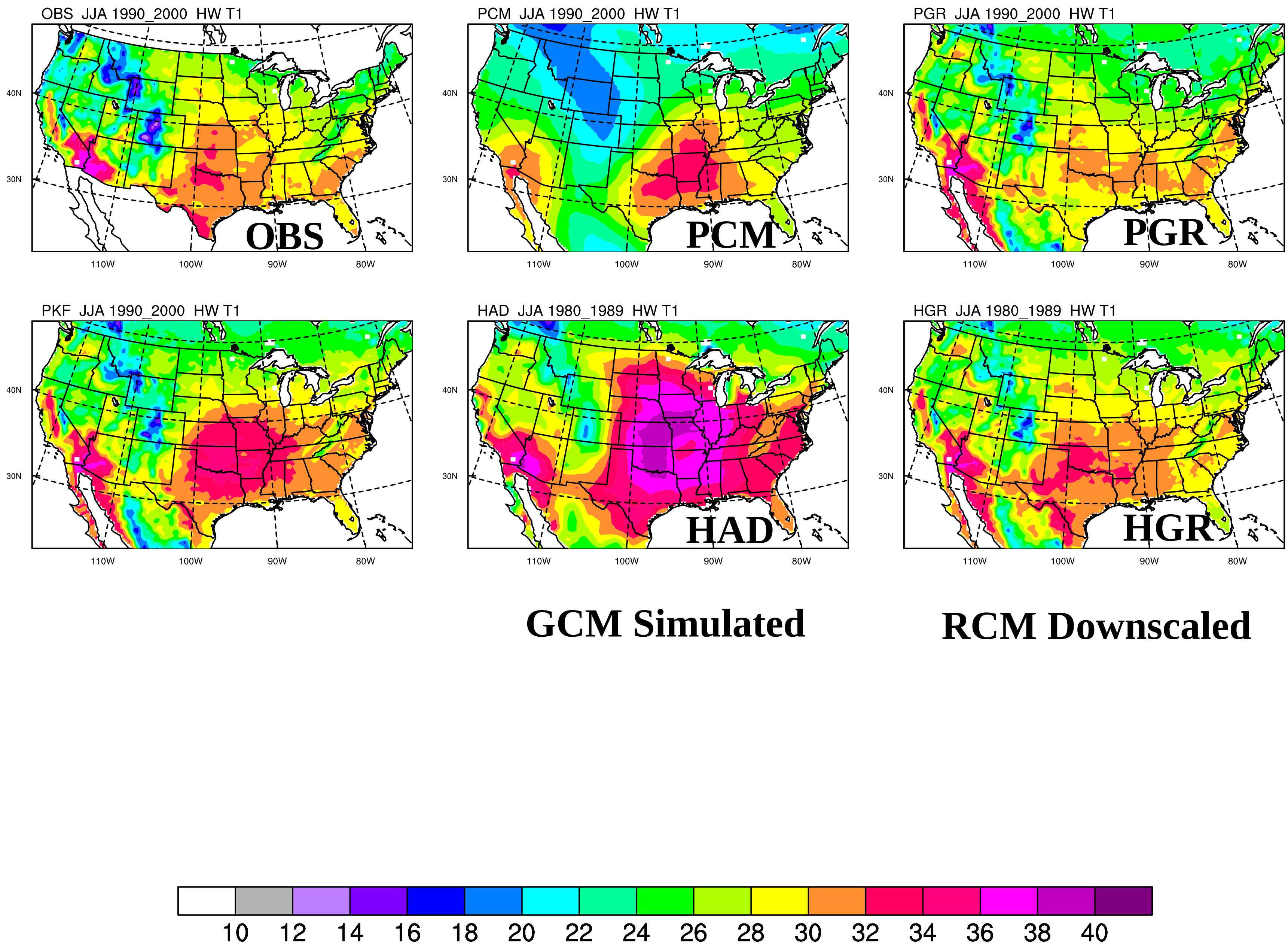
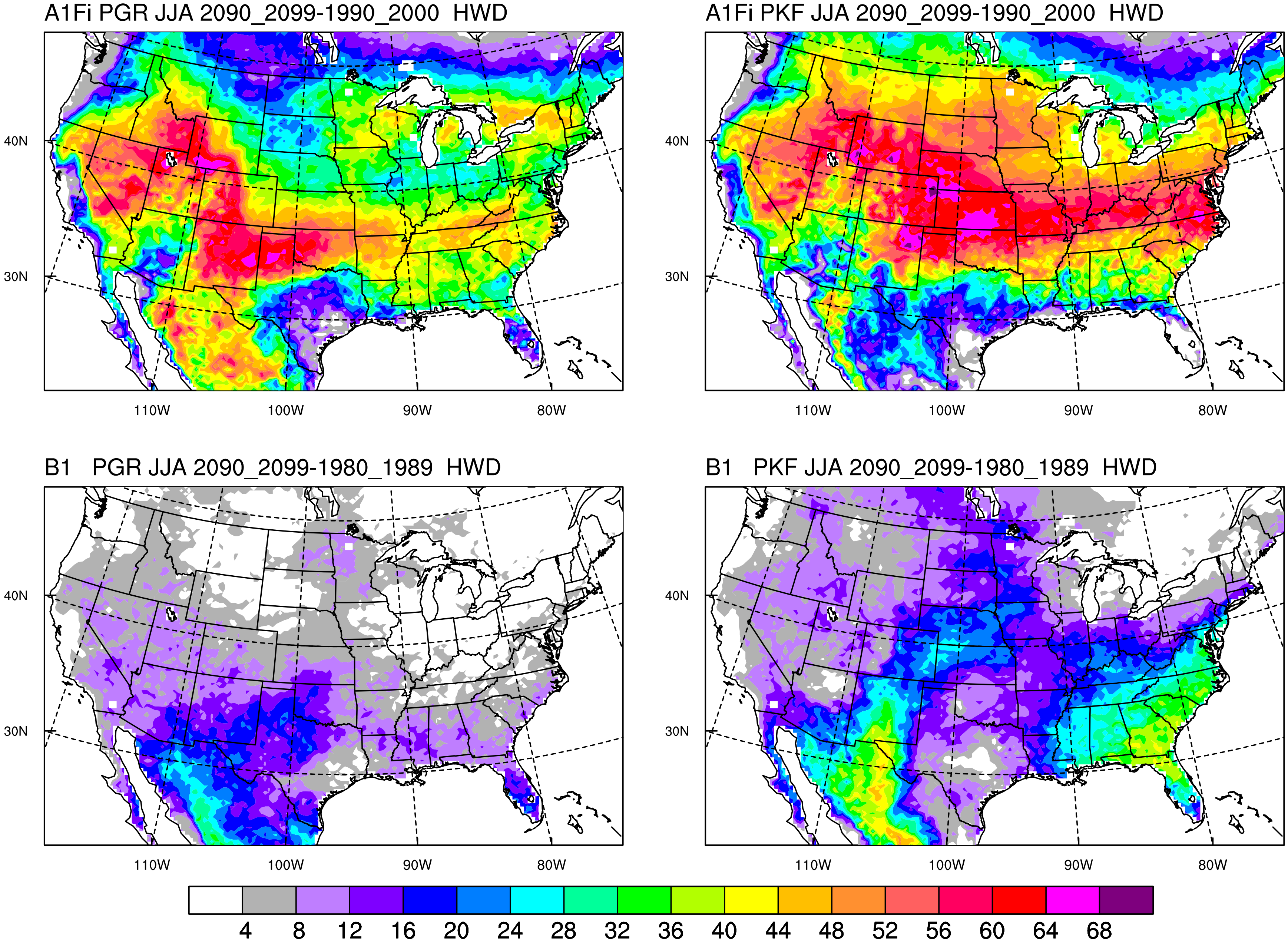
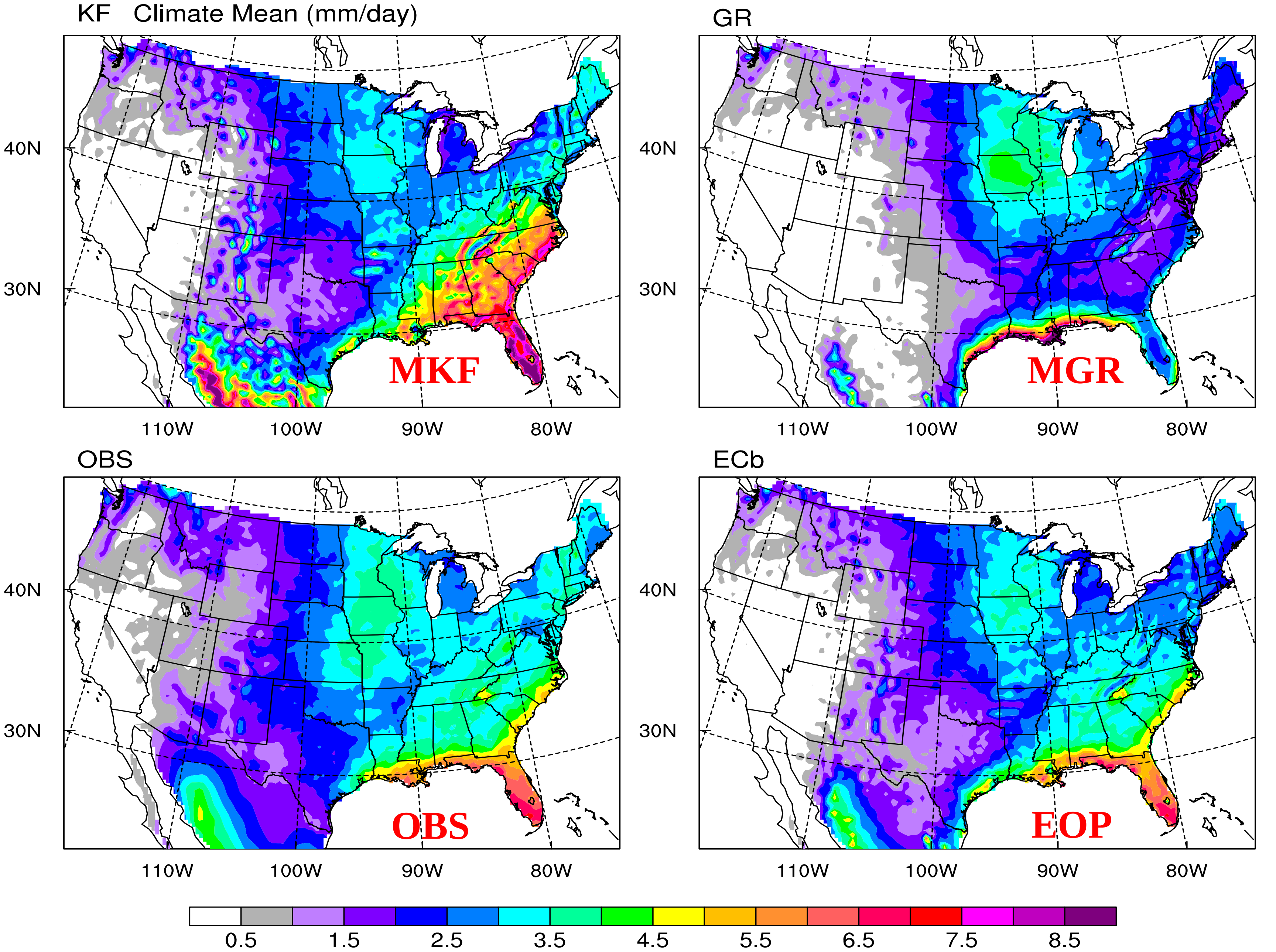
RCM versus GCM Simulated Heat Wave Days



RCM Downscaling Sensitivity to Cumulus Schemes



RCM Ensemble Cumulus Prediction



Air Quality Model Results

The following examples show

- the difference between AQM and CTM in simulating the present ozone and projecting future changes
- the effect of the RCM climate sensitivity on AQM simulations and projections
- the AQM ozone projections for 2100 under different emissions scenarios and incorporating climate changes

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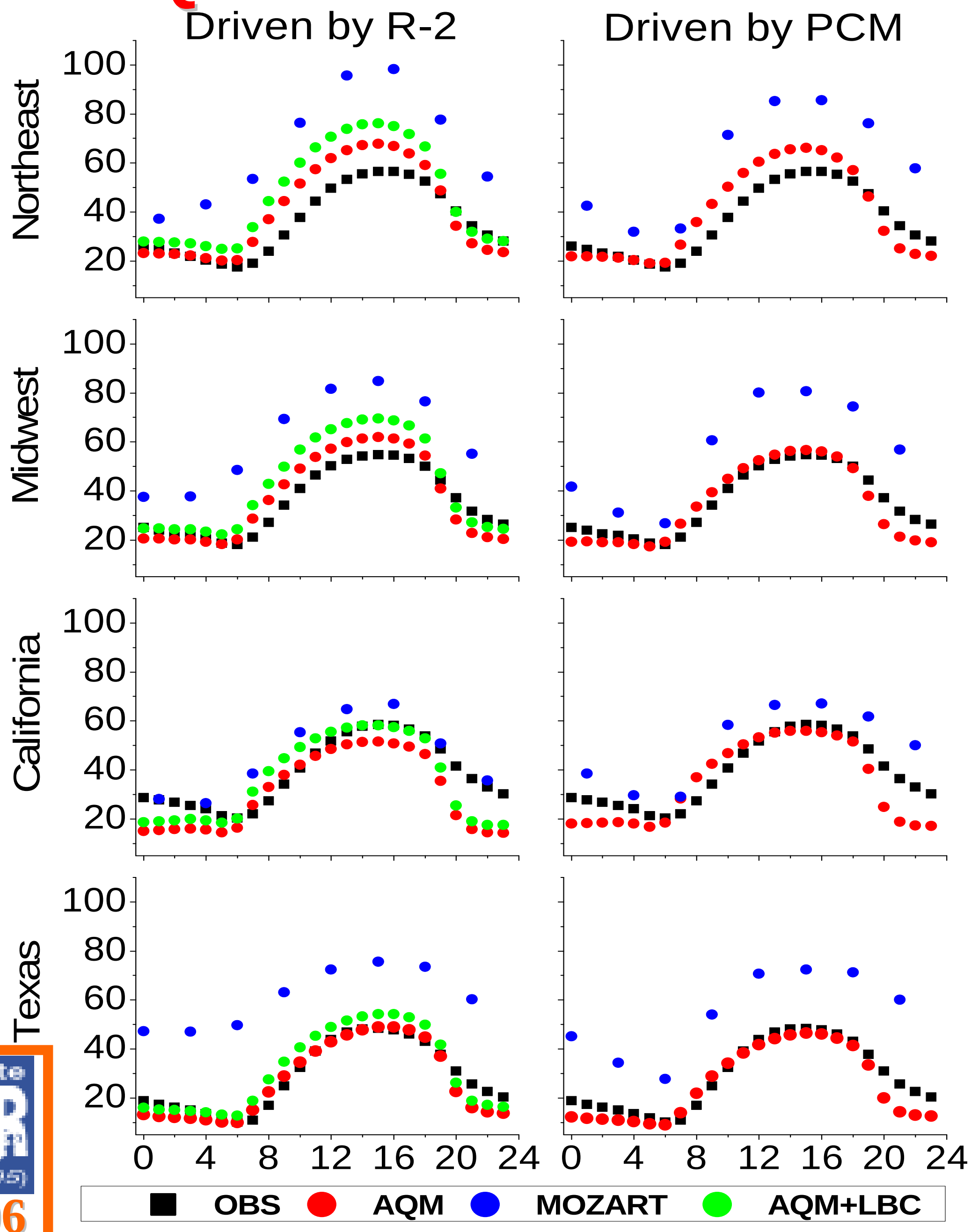
CTM and AQM simulated O3 diurnal cycle



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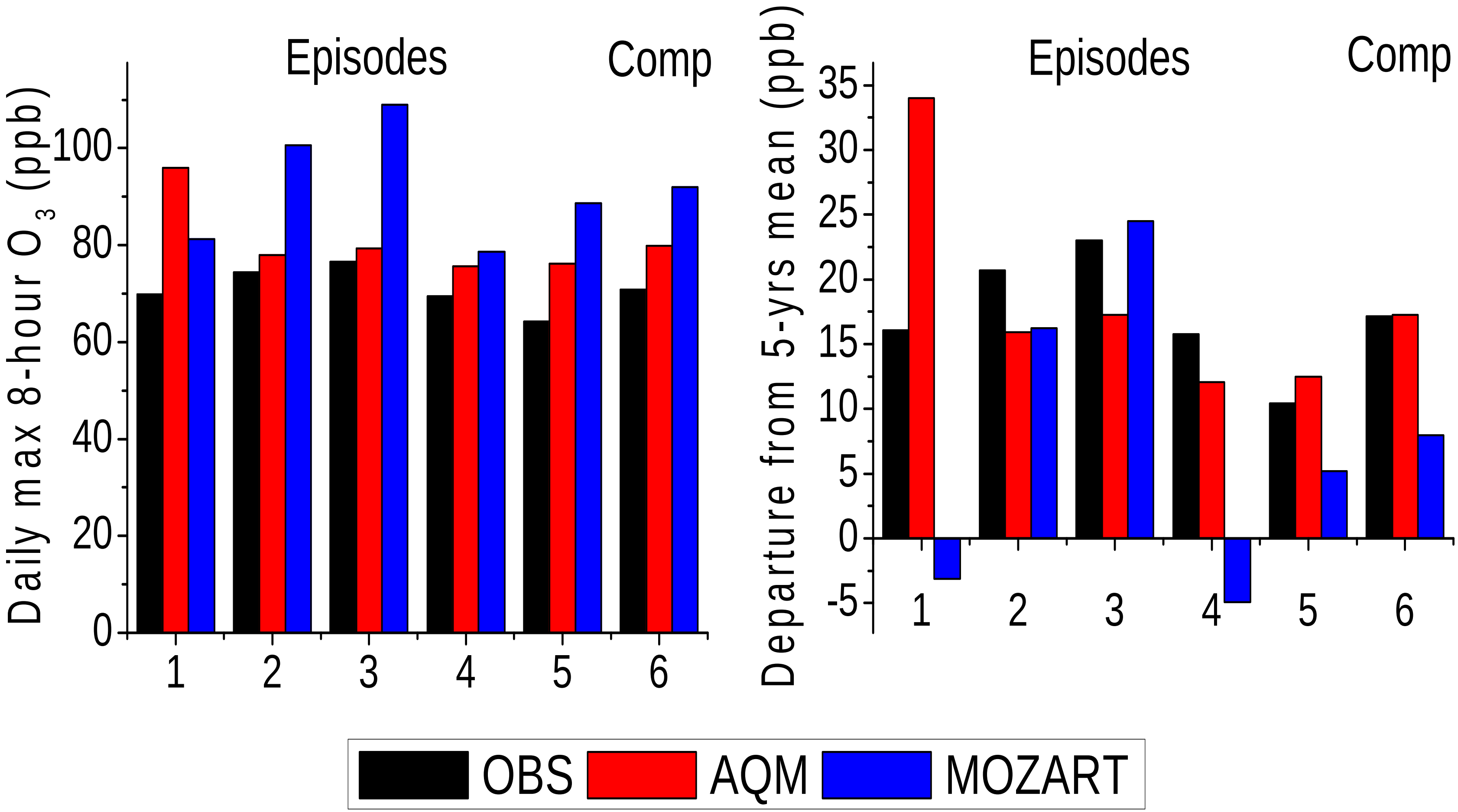
CTM and AQM simulated O3 episodes



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Improvements of model chemistry and physical parameterizations

Comparisons with the observed ozone in 1999 June – August

Control (SMOKE emis.)

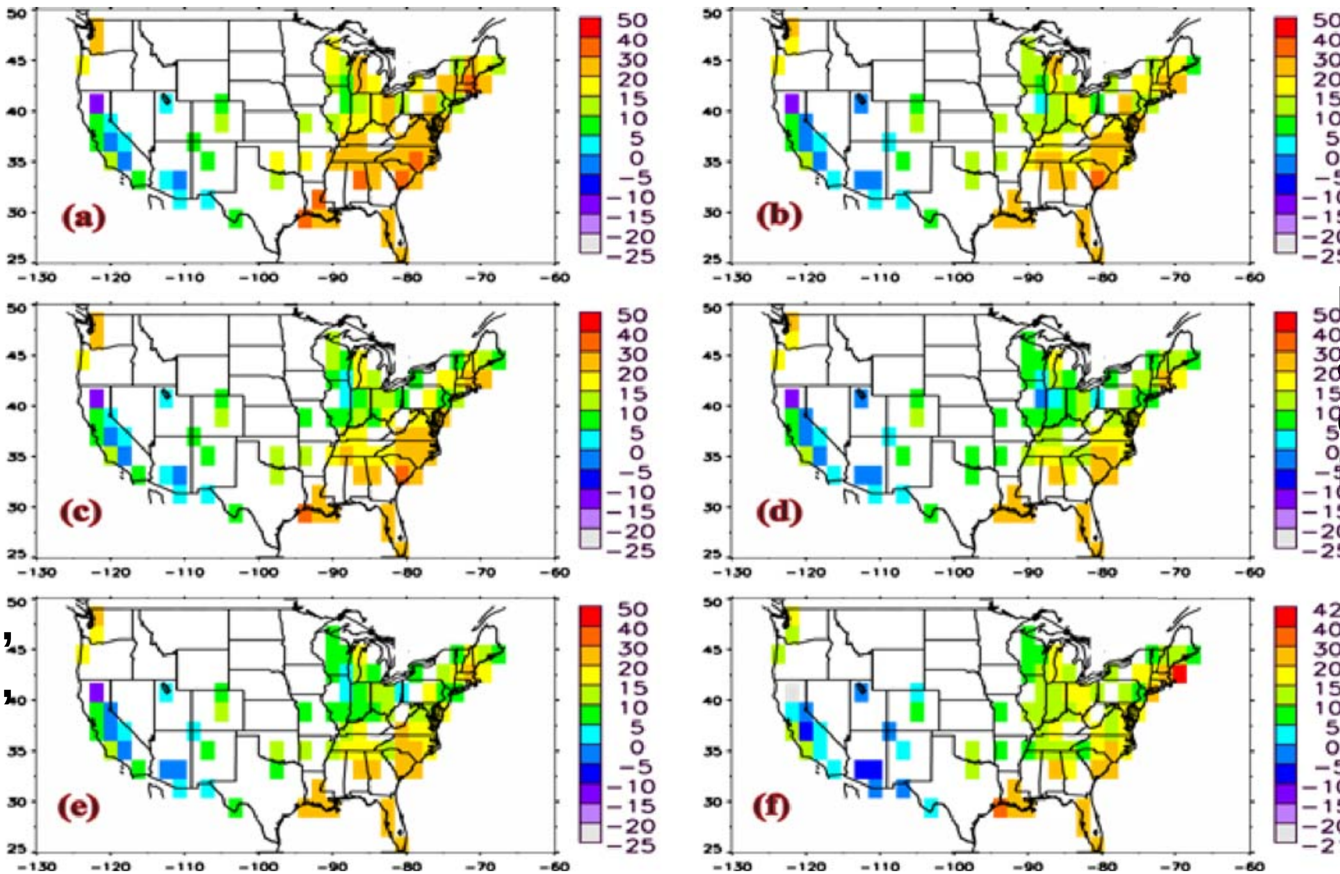
Isop. chem. improved

O3 dry dep. improved

Isop. chem. and O3 dry dep. improved

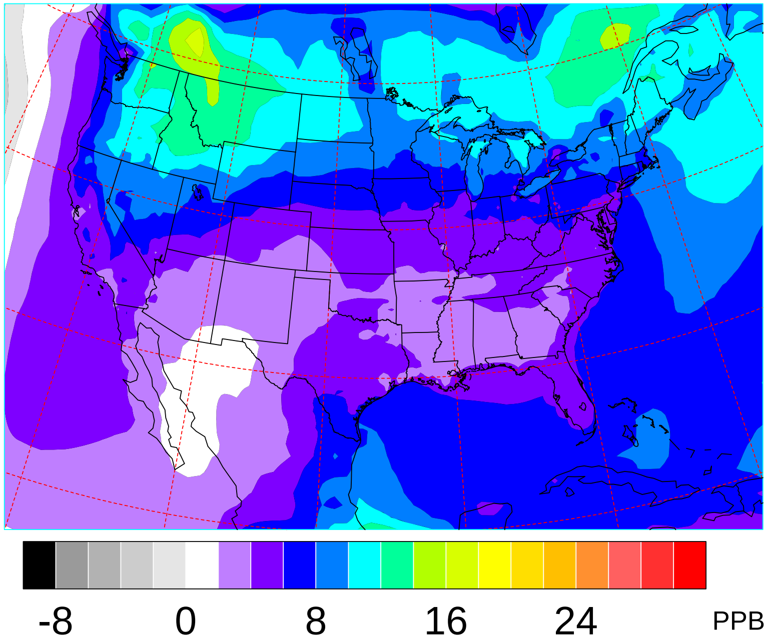
Isop. chem., O3 dry dep., and Rc improved

Isop. chem., O3 dry dep., and Rc improved (MOZART emis.)



- ➢The improvement of the chemistry of isoprene nitrate reduces the model biases of ozone by 5 – 10 ppb over the eastern U.S.
- ➢The improvement of ozone dry deposition parameterization reduces the model biases of ozone by 5 – 10 ppb over the eastern U.S.
- ➢The modification of the critical Richardson number has little effects on ozone.

Long-Range Transport Impact on Local-Regional AQ



The chemical LBCs predicted by MOZART cause AQM to produce overall more O_3 than assuming clean air boundaries. The effect is especially large in northwest U.S., where 10-18 ppb more O_3 may result from the long-range transport.

Long-range transport can exacerbate local and regional air quality problems by elevating the background and loading during episodes.

Overall Regional Uncertainty

The following examples show

- the spread among models of Midwest temperature and ozone biases and future projections under various emissions scenarios

- the sensitivity of ozone temperature-dependence to regional emissions changes

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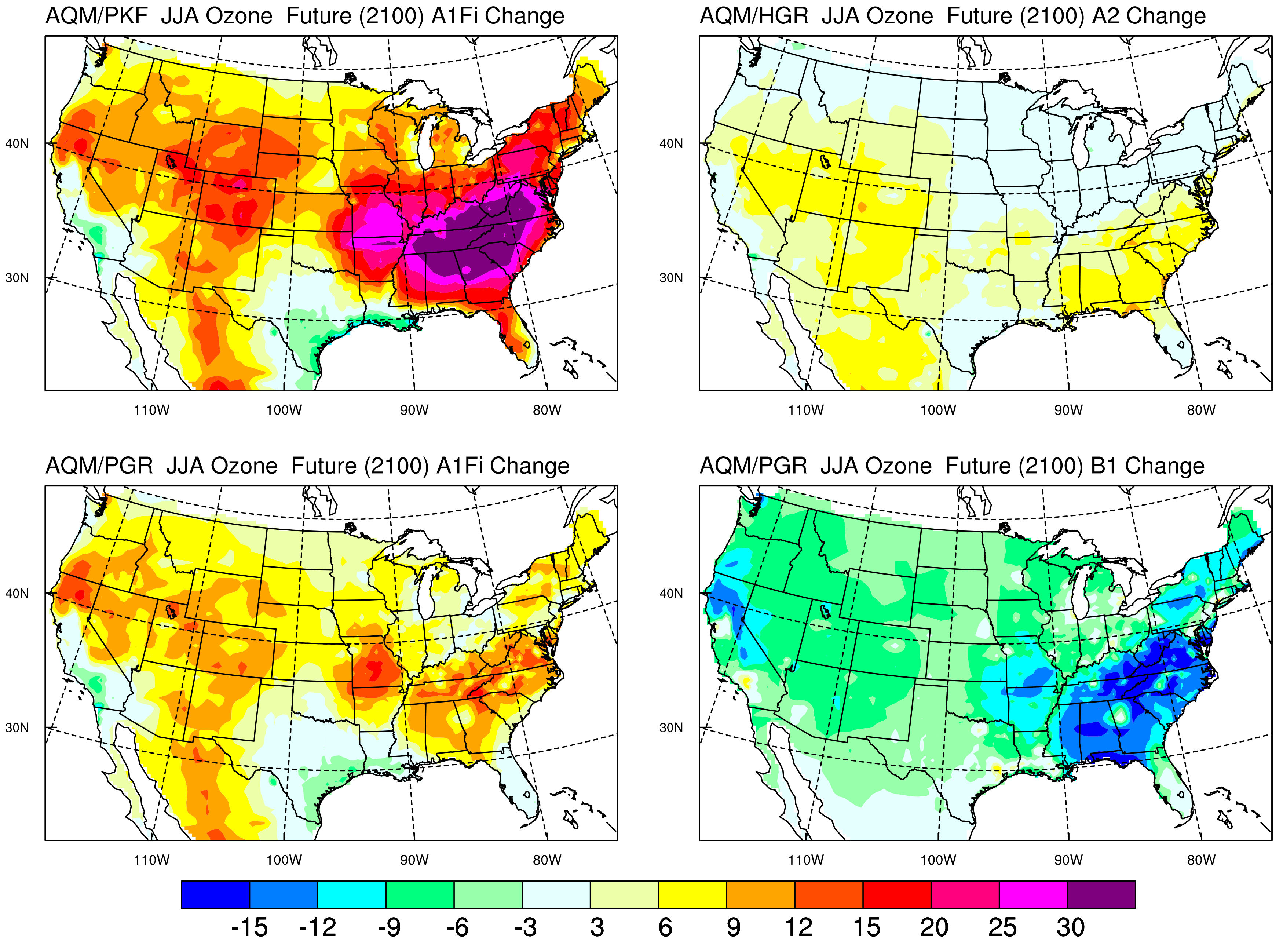
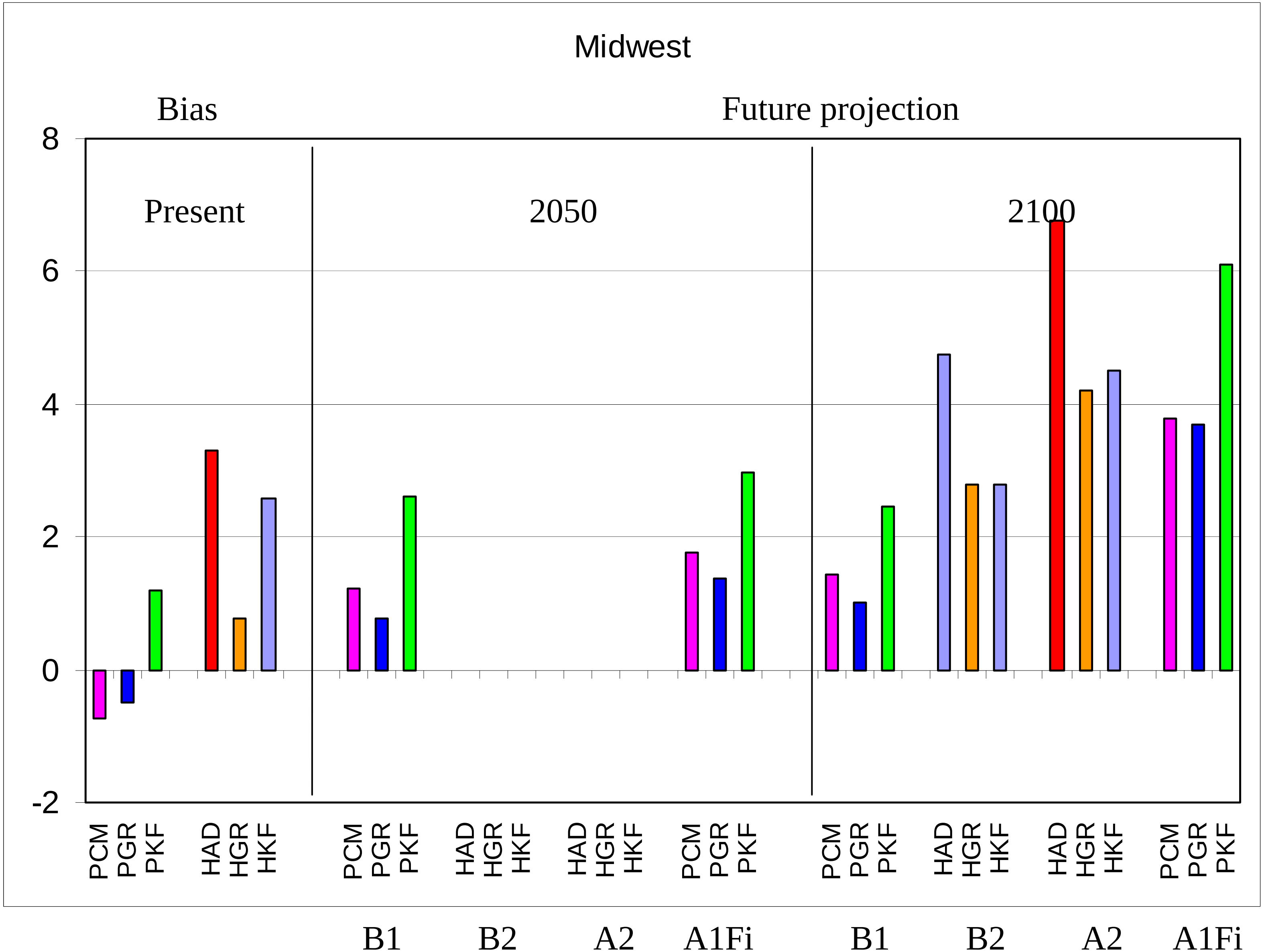
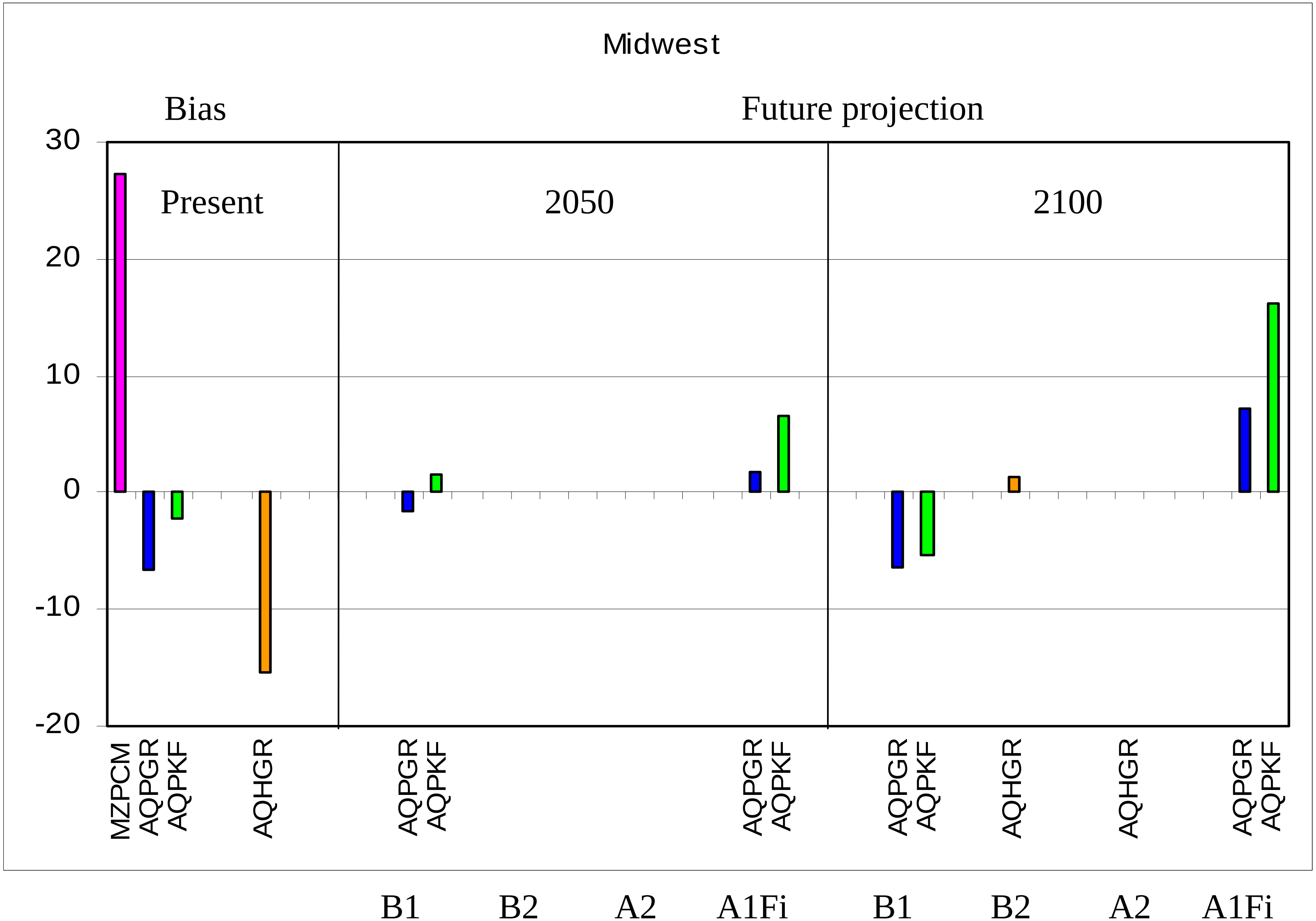


AQM/PKF JJA Ozone Future (2100) A1Fi Change
AQM/HGR JJA Ozone Future (2100) A2 Change
AQM/PGR JJA Ozone Future (2100) A1Fi Change
AQM/PGR JJA Ozone Future (2100) B1 Change
40N
30N
110W
100W
90W
80W
-15
-12
-9
-6
-3
3
6
9
12
15
20
25
30

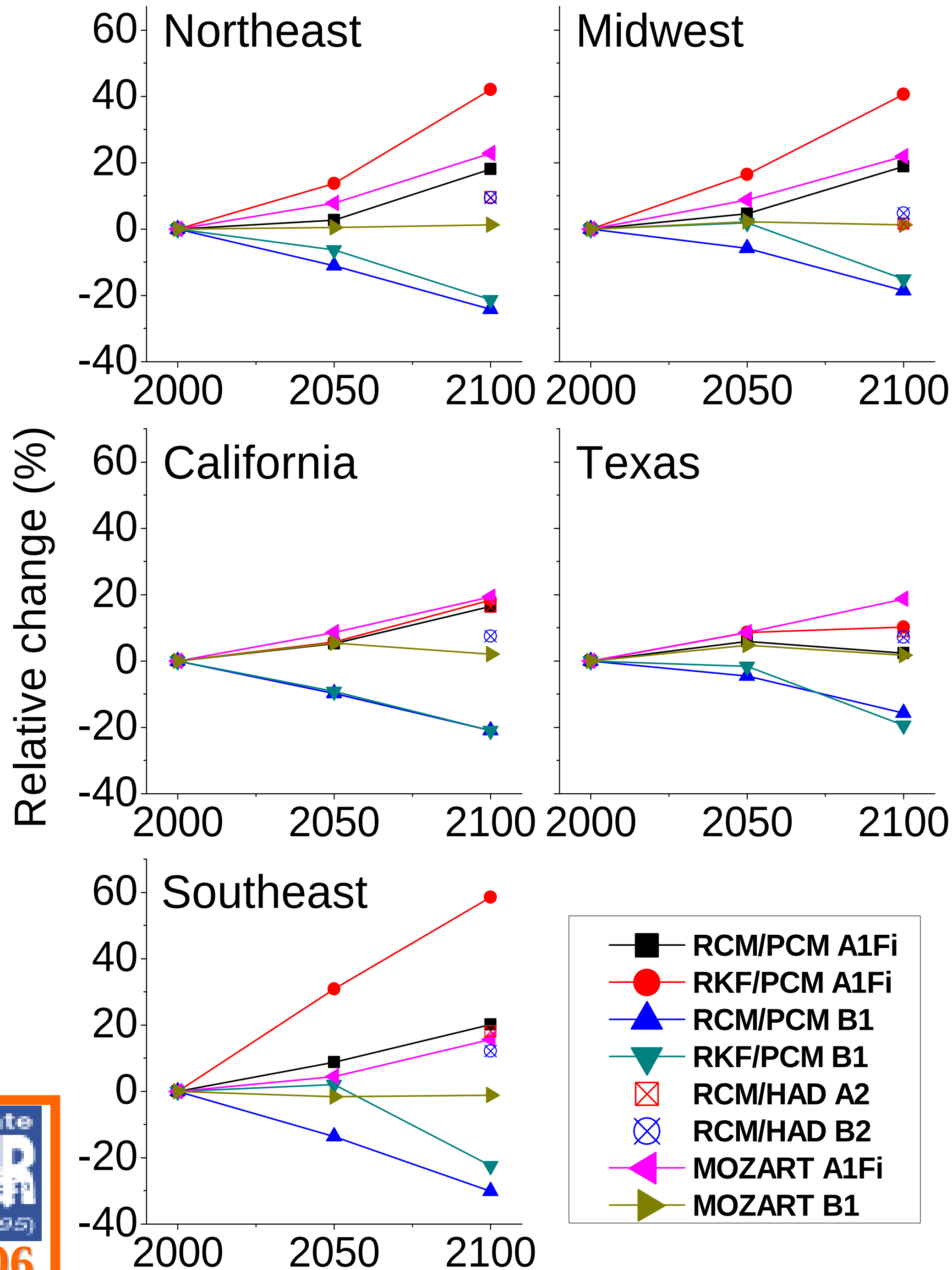
Regional Temperature Bias and Future Projection





U.S. Midwest regional ozone biases and future projections by GCMs (PCM, HAD) and their downscaling RCMs (GR, KF)

Daily Mean [O_3]



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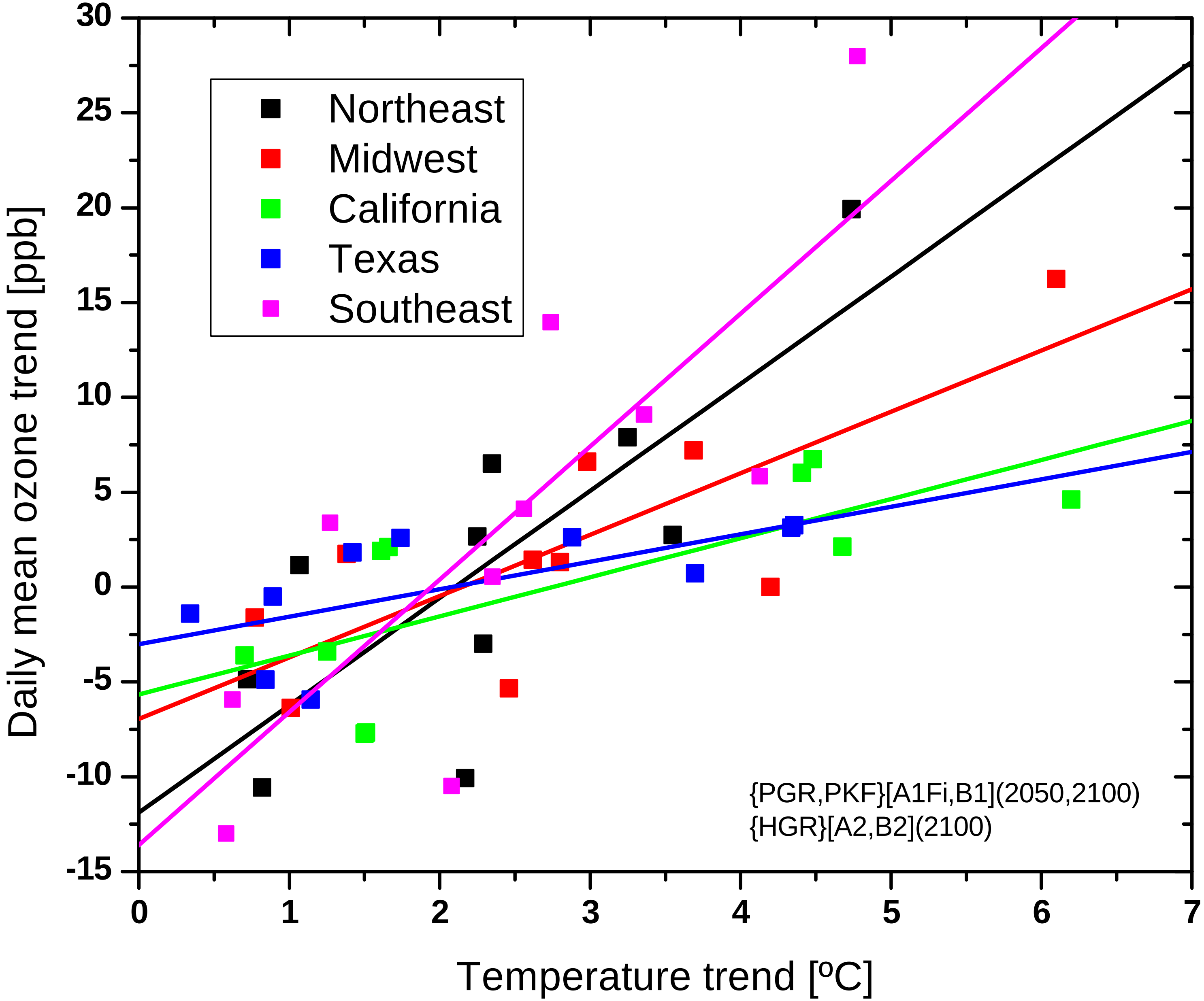
Link between Temperature and Ozone Changes



U.S. background O3 and contributions from nearby/remote sources

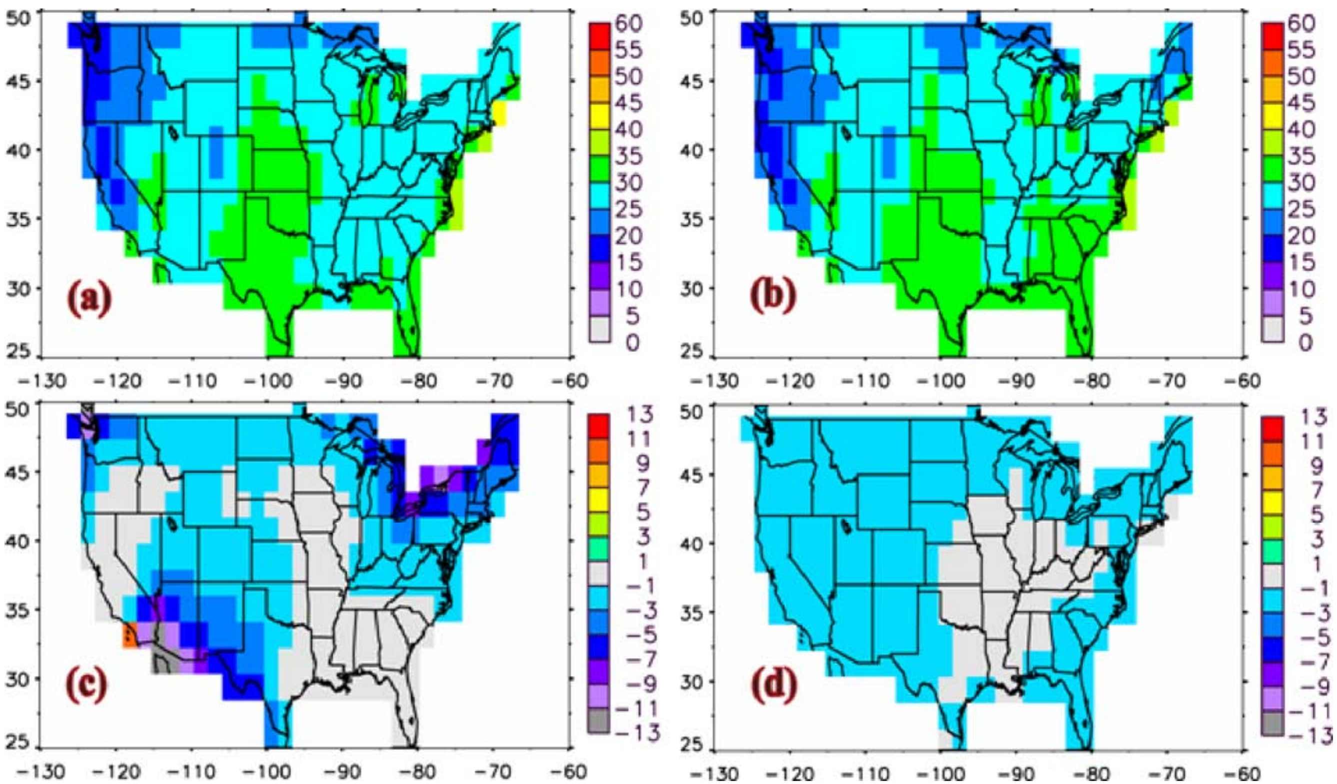
1999 June – August Mean in the Surface Layer

MOZART emissions

SMOKE emissions

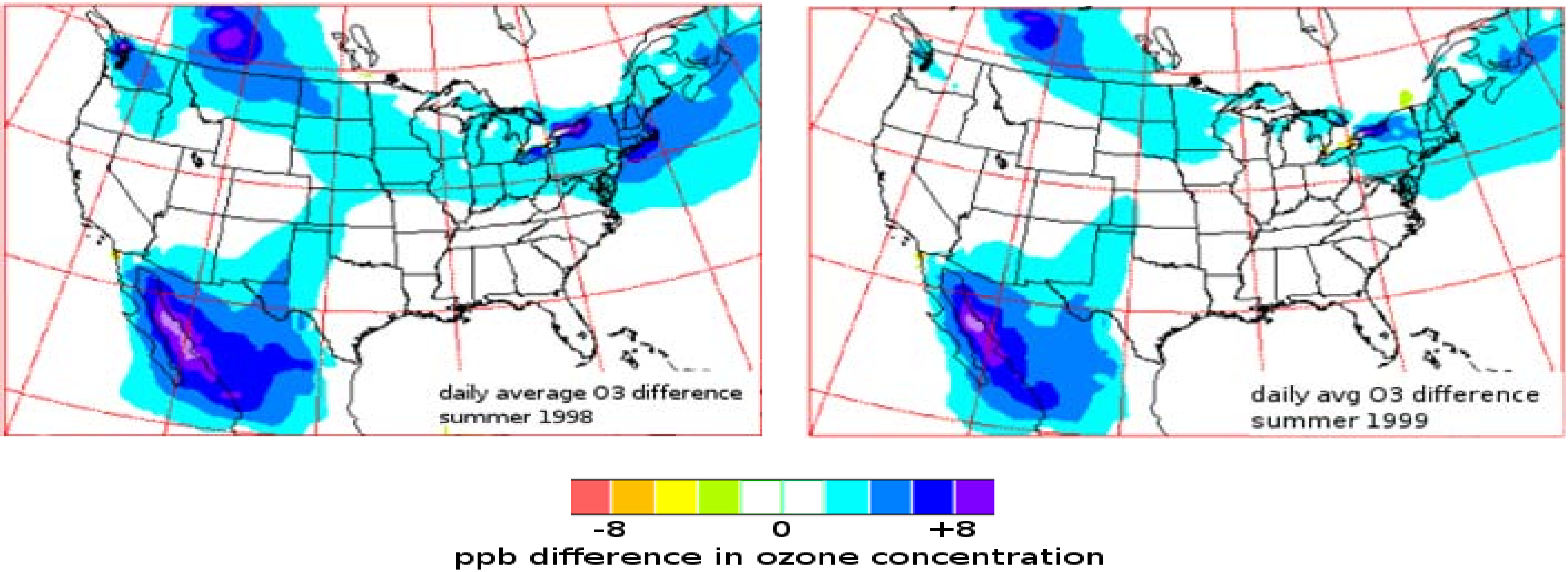
Canada + Mexico

Europe + Asia



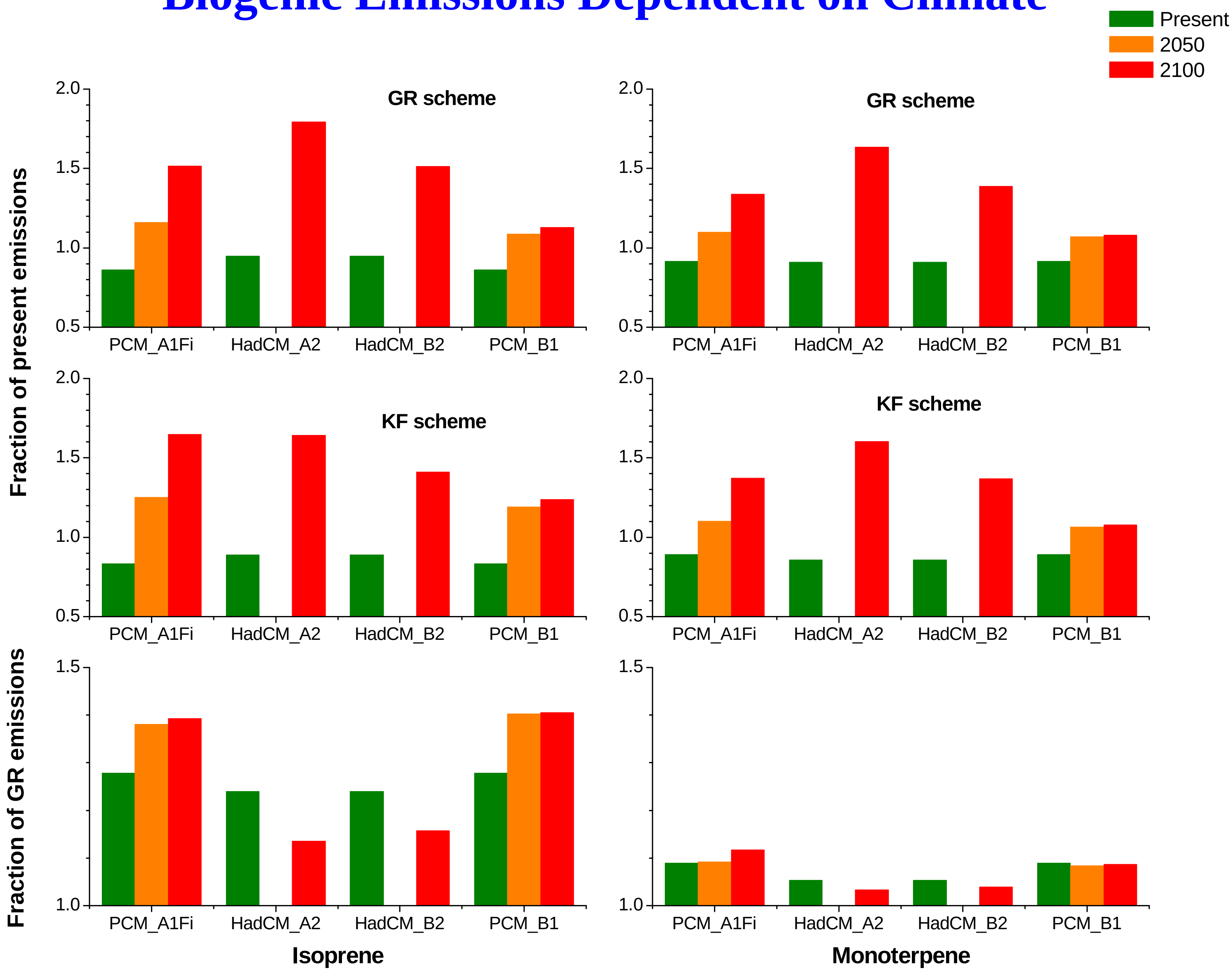
- ➢Current U.S. ozone background ranges from 20 – 40 ppb in summer.
- ➢Anthropogenic emissions from Canada/Mexico contribute up to 13 ppb of ozone near the political boundaries; there is little effect in the central and southeast U.S.
- ➢Anthropogenic emissions from Europe/Asia contribute up to 3 ppb of ozone over the northwest; there is little effect in the central U.S.

Effect of Including Canadian and Mexican Emissions on Simulated 8-hour Maximum Ozone



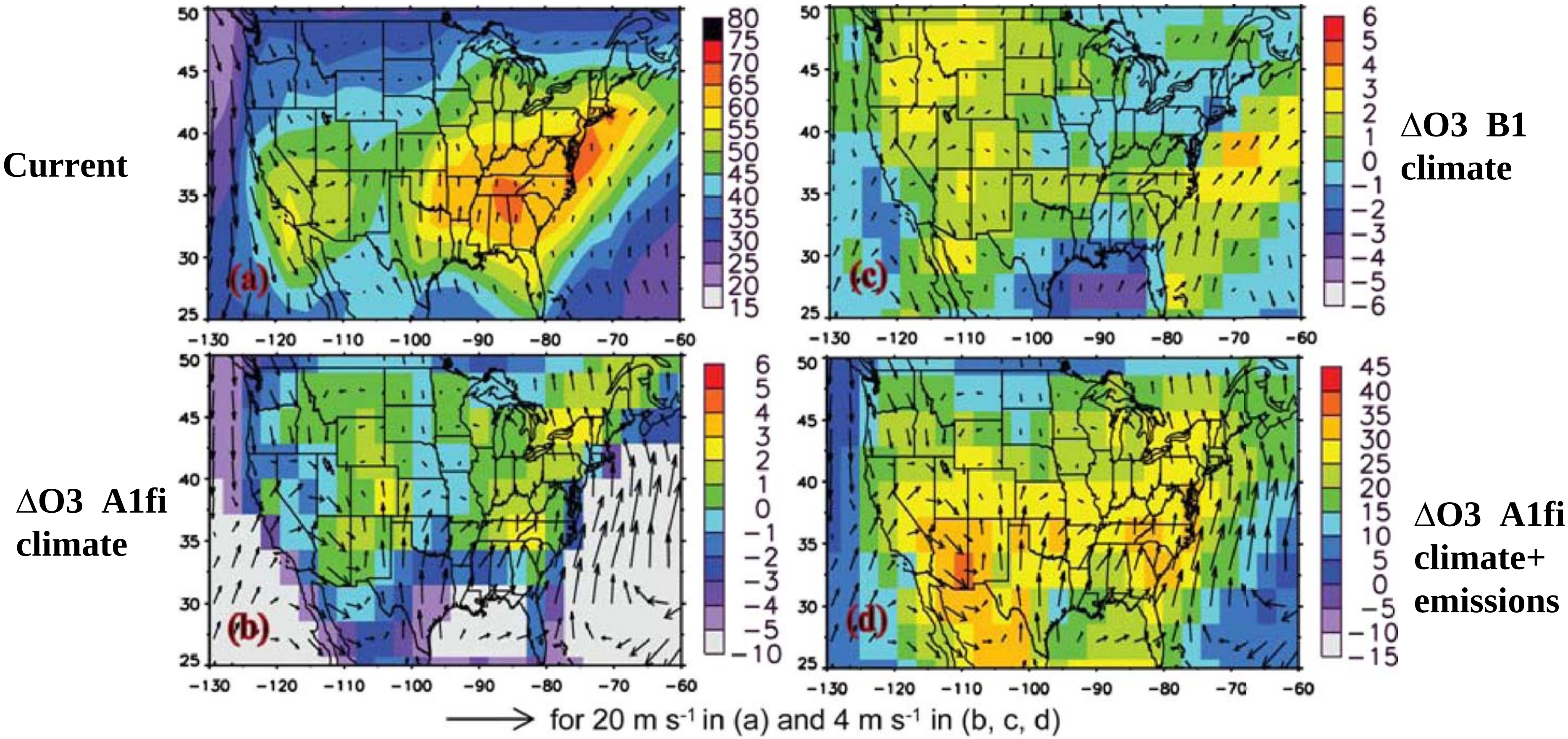
Simulated by regional climate-air quality modeling system (RCM+SMOKE+AQM)

Biogenic Emissions Dependent on Climate



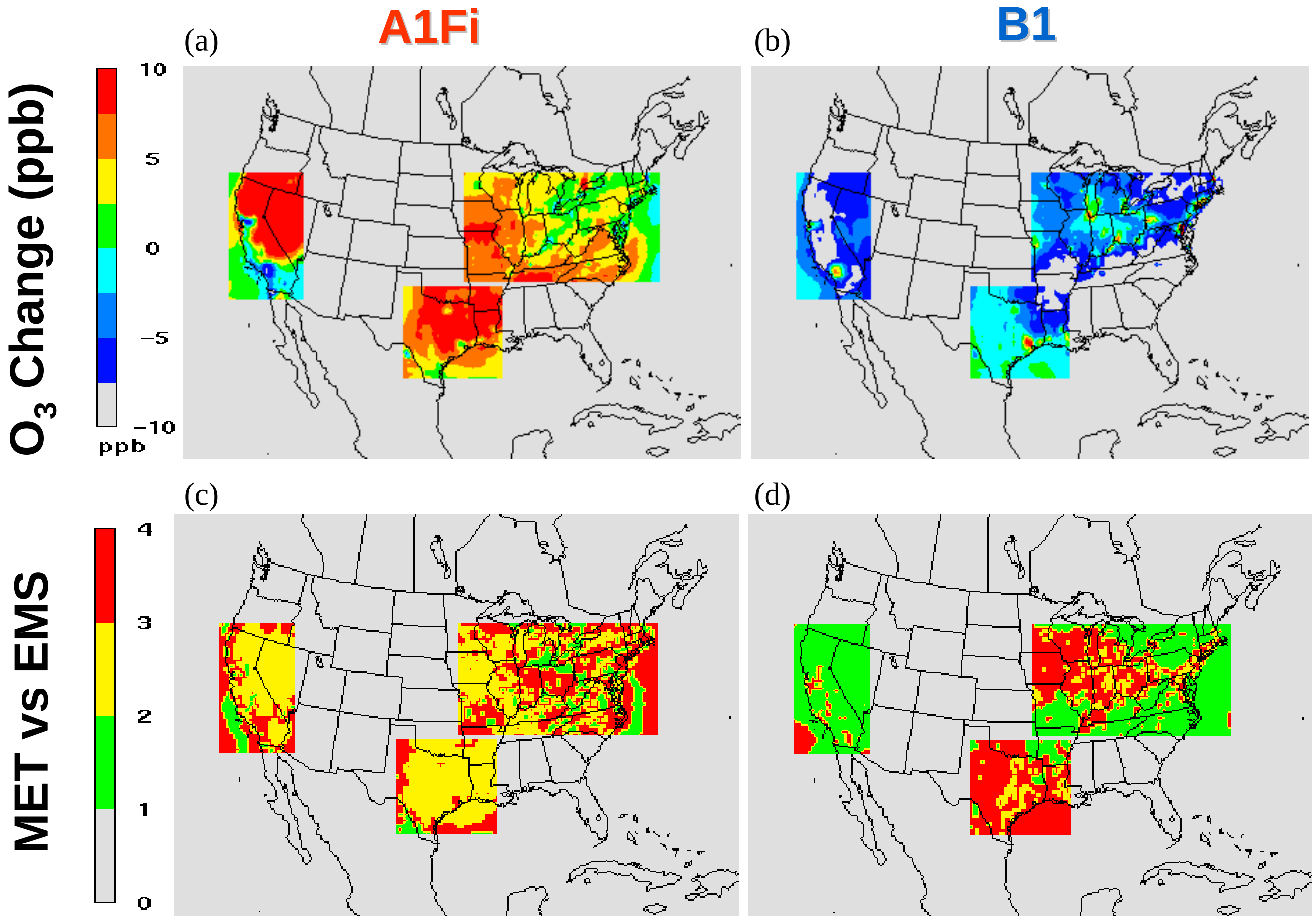
Climate/emission change effects on U.S. regional ozone air quality

June – August Mean in the Surface Layer



- Current ozone levels range from 30 – 70 ppb over the U.S.
- Climate change (only) increase ozone in many inland areas largely due to the increased air temperature; the decrease near the coasts are a result of changes in marine air influence.
- Effects of emission changes, if included, dominate the climate change effects.

Relative Contributions of Emissions & Climate Changes



Summer average daily maximum 8-hour surface ozone concentration changes (ppb) between 2050 and 1998: (a) A1Fi scenario and (b) B1 scenario; and relative contributions (%) of the projected emissions (EMS) and climate (MET) changes to total surface O3 concentration trends between 2050 and 1998: (c) A1Fi scenario and (d) B1 scenario. The color code 1 **(green)** denotes for the dominance of the EMS effect (contribution > 70%), 2 **(yellow)** for that of the MET effect (contribution > 70%), and 3 **(red)** for both effects to be comparable.

Conclusions

[1] Precipitation processes modulate surface temperature and are closely associated with moist convection, thunderstorm activity, cloud formation, and boundary layer development. Collectively they control regional-local variation of air quality processes. We have demonstrated that the RCM downscaling substantially improves precipitation prediction (Liang et al. 2004a-b, Hayhoe et al. 2006, Zhu and Liang 2005, 2006) by capturing the dominant regional and local forcing processes.

[2] The coarse grid spacing and incomplete physics representation cause substantial GCM biases and inter-model differences at regional-local scales (Kunkel and Liang 2005, Kunkel et al. 2006). The RCM driven by 2 GCMs, PCM and HadCM3 with low and high climate sensitivity, significantly reduces the biases and inter-model differences in simulating the present climate and has important consequence on projecting future climate. The result suggests that the GCMs are adequately simulating large-scale circulation patterns for realistic RCM downscaling (Liang et al. 2006) but that the RCM downscaled future climate changes may be more credible.

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Conclusions

[3] The AQM driven by SMOKE emissions and RCM meteorology faithfully reproduces the observed U.S. summer ozone variations (Huang et al. 2006a-d) while the CTM produces much larger positive ozone biases over most of the central-eastern U.S. (Lin et al. 2006) and considerably greater errors in ozone episodes. As a result, the AQM and CTM simulate very different U.S. ozone responses to the projected climate and emissions changes under same scenarios and the mesoscale modeling system is a more credible tool.

[4] Long-range transport of global pollutants and precursors has important effects on U.S. air quality, especially across the Canadian and Mexican borders (Huang et al. 2006c). More rigorous validation and improvements to reduce CTM biases along the boundaries are needed before its outputs can be credibly used to provide chemical LBCs for the AQM downscaling.

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Conclusions

[5] Relative contributions of climate versus emissions changes on U.S. air quality strongly depend on the projecting scenarios. For A1Fi, emissions and climate changes contribute about equally to the projected ozone responses. For B1, the impact from climate changes is much smaller than from decreased emissions. Present anthropogenic emissions from Canada and Mexico contribute to U.S. background ozone more than from Europe and Asia (Lin et al. 2006). However, future ozone increases in China (Southeast Asia) under A1Fi (B1) are projected to contribute more to U.S. background, increasing the difficulty in attaining the national standards.

[6] The RCM downscaling skill is sensitive to the choice of cumulus parameterization. The Grell scheme better reproduces rainfall in the Midwest, while the Kain-Fritsch scheme is more realistic over the Southeast and in the North American Monsoon region (Liang et al. 2004a,b, Zhu and Liang 2006). Consequently, there are large impacts in simulating biogenic VOC emissions and ozone concentrations. The Kain-Fritsch scheme yields much higher isoprene emissions (Tao et al. 2006) and the AQM produces greater ozone biases (Huang et al. 2006b).

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Conclusions

[7] The uncertainty in projecting future U.S. air quality is substantial, especially by 2100, arising from the estimate of emissions changes, the climate sensitivity of GCMs and RCMs, and the chemistry mechanisms of CTMs and AQMs. Changes range from substantial increases under A1Fi to large decreases under B1. If no control is taken to avoid high emissions like A1Fi, the Northeast and Midwest are likely to suffer a greater risk of future air quality degradation than California and Texas, while the Southeast, showing greater sensitivity to both climate and emissions changes, has the greatest risk of violating the national ozone standard.

[8] We have so far 6 articles published, 3 articles accepted or in press, 3 articles submitted, 3 manuscripts almost completed, and are preparing several others for publication in peer-reviewed journals. We have also made over 30 presentations in key research institutions (invited seminars) and major conferences including the U.S. Climate Change Science Program workshop, the EPA Assessment of the Impact of Global Change on U.S. Air Quality workshop, the American Geophysics Union, the American Meteorology Society and the American Association for the Advancement of Science annual meetings.

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Impacts of Global Climate and Emissions Changes on U.S. Air Quality (Ozone, Particulate Matter, Mercury) and Projection Uncertainty

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2007-2010

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Objective

To quantify and understand the impacts and uncertainties of global climate and emissions changes, from the present to 2050 and 2100, on U.S. air quality, focusing on O_3, PM and Hg.

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Approach

Apply a unique, state-of-the-art, well-established *ensemble* modeling system that couples a global climate-chemical transport component with a mesoscale regional climate-air quality component over North America. Both components incorporate multiple alternative models representing the likely range of climate sensitivity and chemistry response under the conceivable emissions scenarios to rigorously assess the result uncertainty. Each will be enhanced to contain a fully coupled model to study climate-aerosol interactions, focusing on how they affect U.S. air quality at the present and in the future.

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Contribution

- **Quantify the effects of global climate and emission changes on U.S. air quality and uncertainty**
- **Provide a more complete scientific understanding of the complex interactions among global climate and emissions and U.S. air quality across a full range of spatial and temporal scales**
- **Consolidate ozone, elaborate aerosol and explore mercury studies for use in designing future effective emission control strategies to meet the national ambient air quality standards**

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EPA STAR 2007-2010

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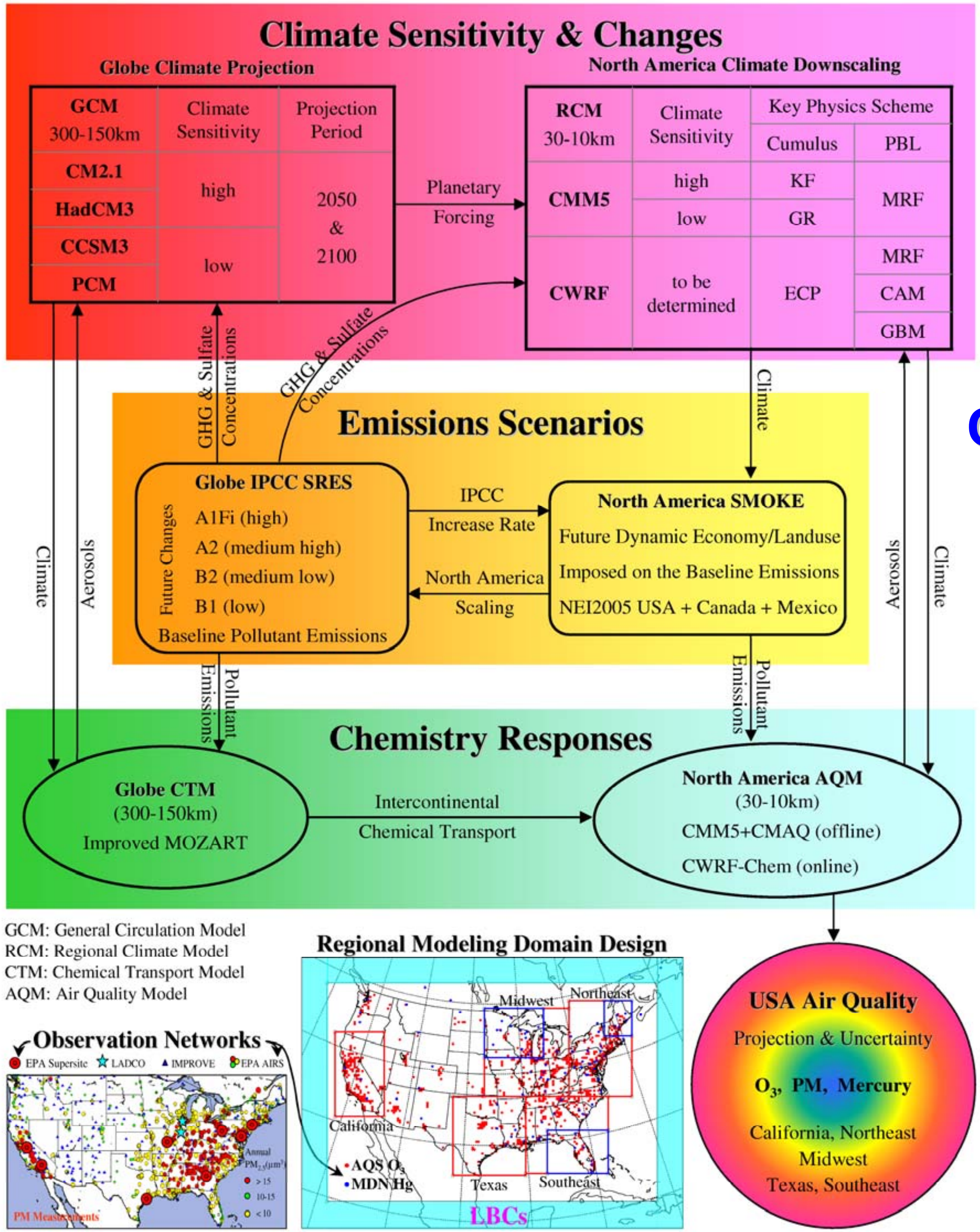

FOCUS

Consolidate
O_3

Elaborate
PM

Explore
Hg

Building Foundation

Recent achievements of our O_3 study, EPA STAR 2003-2006, including:

- Developed modeling system
- Viable experiment design
- Effective modeling strategy
- Objective diagnostic approach

Consolidation of Ozone Study

- **Biogenic Emissions with Dynamic Vegetation**
  - Agro-IBIS (Donner and Kucharik 2003) for land cover/use changes
  - MEGA (Guenther et al. 2006) for VOCs biogenic emissions changes
- **CTM Bias Reduction in U.S. Ozone and Long-Range Transport**
  - Emissions data (SMOKE diurnal/daily/interannual variations, point sources)
  - Model resolution (avoid smoothing subgrid emissions and concentrations)
  - Chemical processes (reactions rates for isoprene nitrates and hydroxyl radical, dry deposition velocity, PBL mixing, stratosphere-troposphere exchange, aerosol processes)
- **Representative GCM Projected and RCM Downscaled Climate Changes**
  - systematically address climate changes and uncertainty by 32 combinations:
  - 2 GCMs' projections under 4 emissions scenarios
  - 2 RCMs' downscaling with 2 cumulus or PBL parameterizations

Elaboration of PM Study

- **Source Emissions for Aerosols and Precursors**
  - Adopts latest static and dynamic emissions for anthropogenic and natural sources
- **MOZART-4 Intercontinental Transport of Aerosols and Precursors**
  - Aerosols transport over long distances, even across continents, by MOZART-4
- **CMAQ and CWRF-Chem Representation of Aerosols Dynamics**
  - Modal approach in CMAQ v4.5.1 for major applications
  - Sectional approach in CMAQ v4.4 for sensitivity study on uncertainty
  - CWRF-Chem online coupled climate-air quality interaction
- **Climate-Aerosol Interactions**
  - CWRF-Chem integrates long-range transport of aerosols and precursors simulated by CCSM3-MOZART via LBCs forcings
  - Separate the effects of aerosols transported from remote sources versus those originating from regional-local sources

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Exploration of Mercury Study

- **Mercury Emissions with Dynamic Parameterizations**
  - Anthropogenic Hg emissions by NEI2005 for major point , area sources in U.S., Canada, Mexico
  - Natural Hg^0 emissions parameterized dynamically for soil, vegetation and surface water
- **CMAQ Mercury Chemistry into MOZART-4**
  - Represent mercury chemistry in the gaseous and aqueous phases in CMAQ v4.5.1
  - Implement the most-updated CMAQ mercury chemistry into MOZART-4
  - Integrate global transport via LBCs from MOZART-4 for CMAQ downscaling
- **Process Understanding for Mercury Changes**
  - Explore the relationships among the processes that affect atmospheric mercury species (Hg^0, Hg_p, RGM), surface emissions (natural, anthropogenic, reemitted), atmospheric transport (local to global), and deposition (dry, wet)
  - Study the crucial roles of convection and clouds in vertical redistribution, in-cloud transformation, and wet removal of atmospheric mercury
  - Focus on 3 regions: upper Minnesota-Wisconsin, New England-Canada and Florida

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